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GB 2218857 A EP 0234663 A1 EP 0160868 A2
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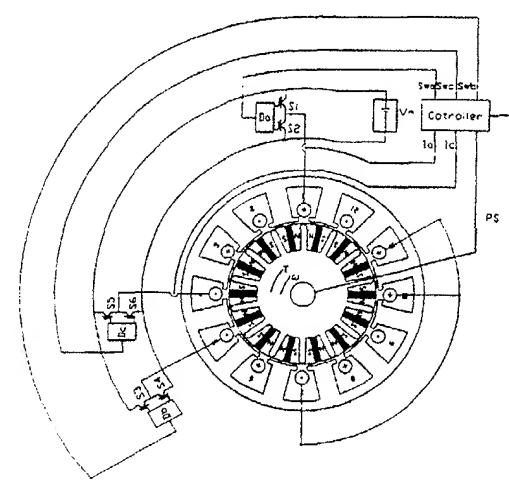
(54) A permanent magnet dc motor and control arrangement

(57) The motor is constructed with the number of magnetic poles equal to the number of stator slots plus or minus two and the stator coil span equals one slot pitch, there being only one phase coil under each magnetic pole so that the magnetic path of the flux produced by each phase current is independent. The rotor comprises a compact construction achieved with a non-magnetic sleeve 4, mounting steel stampings 2, 3 and permanet magnets 1 slide into the slots so formed. End plates retain the assembled magnets. Speed control at constant torque and power regimes is achieved by controlling the field and torque component currents.



ω^* - speed reference
PS - rotor position sensor
I_a, I_c - current feedback
S_{wa}, S_{wb}, S_{wc} - switching signal
D_a, D_b, D_c - driver
S_1, ... S_6 - power switching device
V_m - power supply

(a) Motor and controller configuration

Fig. 1 Basic configuration and principles

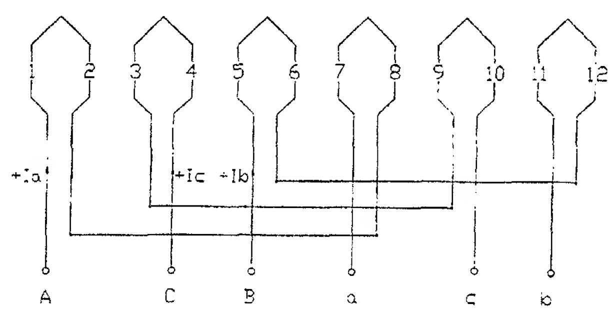
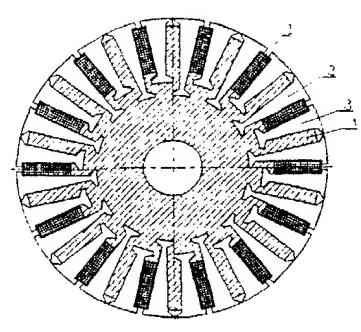


Fig. 2 Winding connection diagram



1 - Permanent Magnet
2 - Rotor Stamping
3 - Rotor Stamping
4 - Rotor Sleeve

Fig 5 Rotor Assembly

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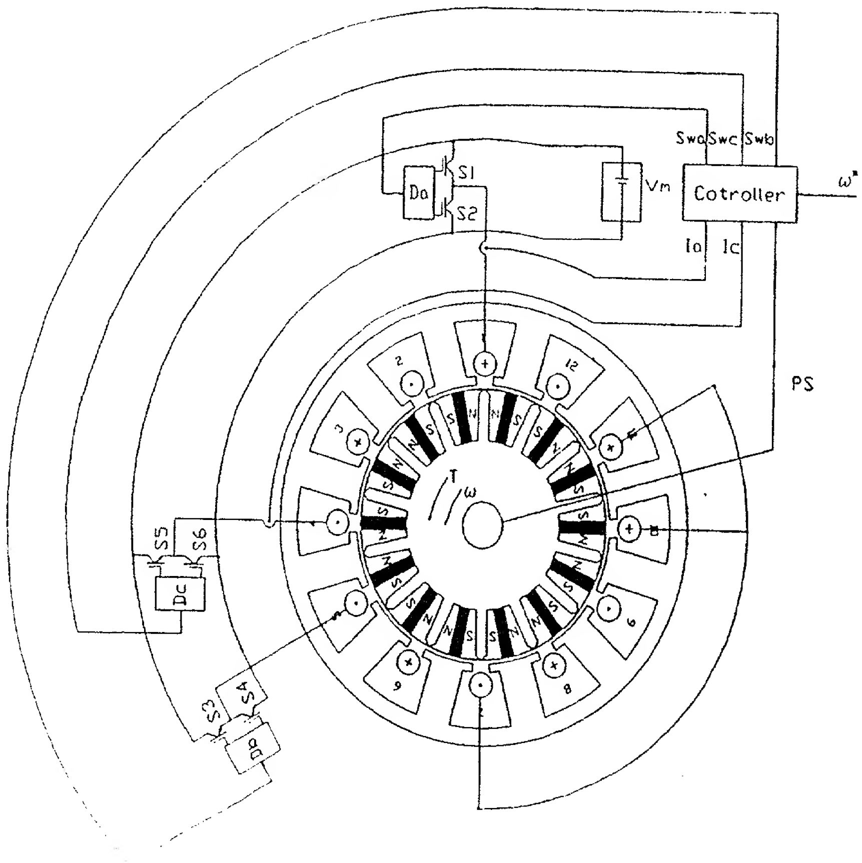

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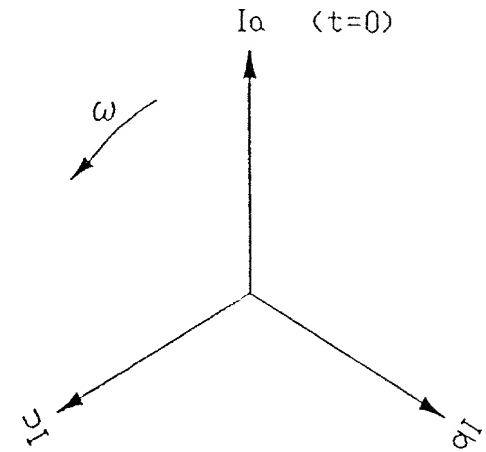
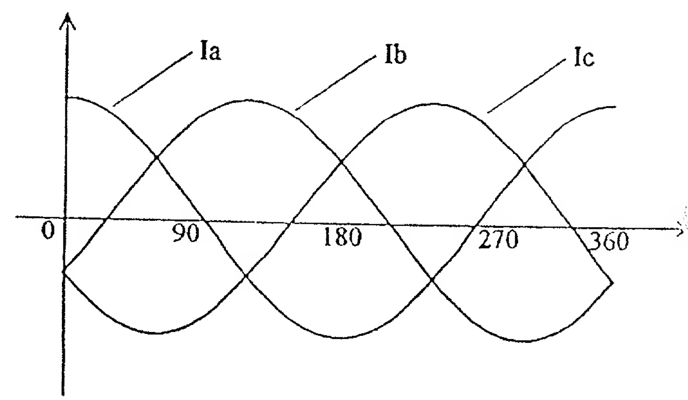
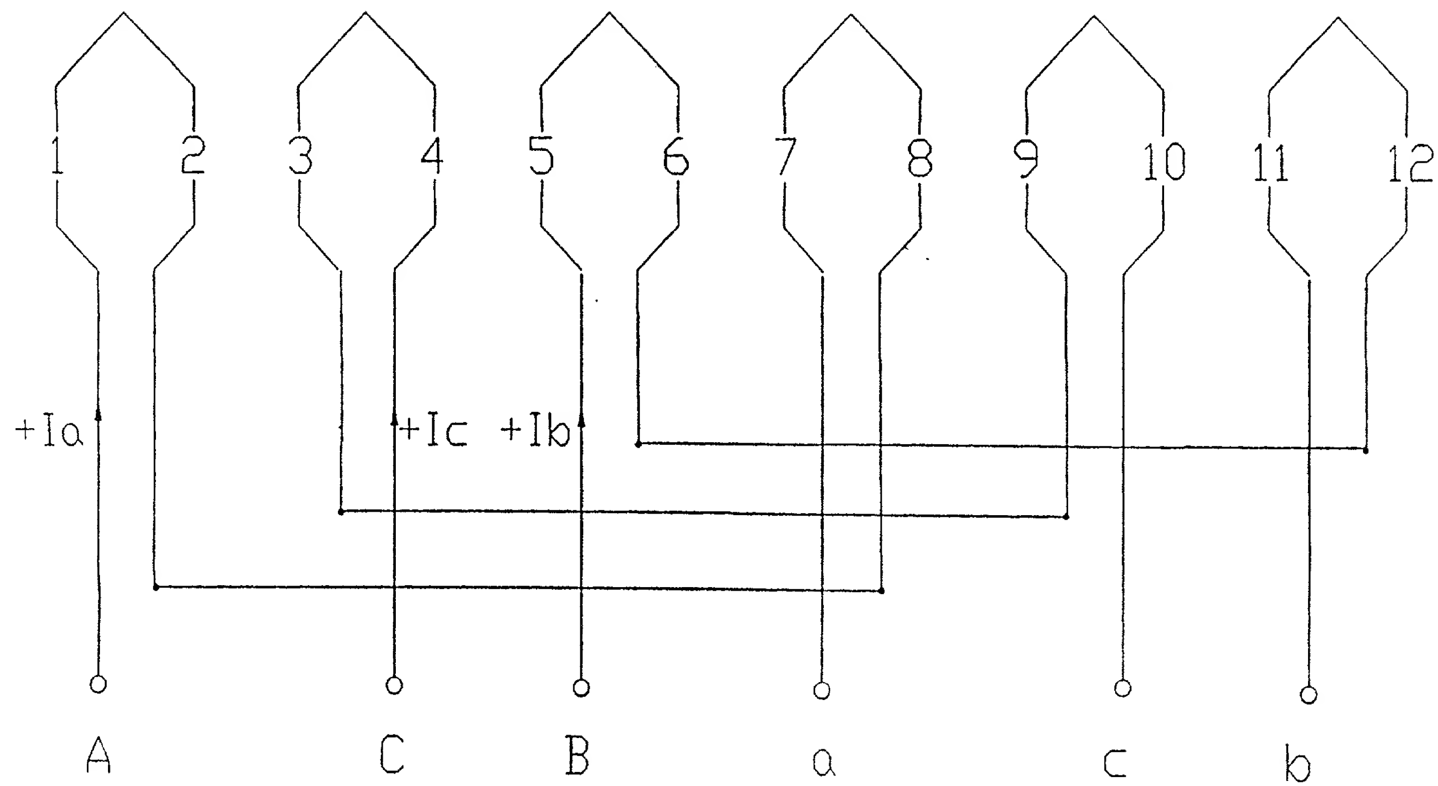


(b) Phasor diagram



(c) Current waveform

Fig. 1 Basic configuration and principles



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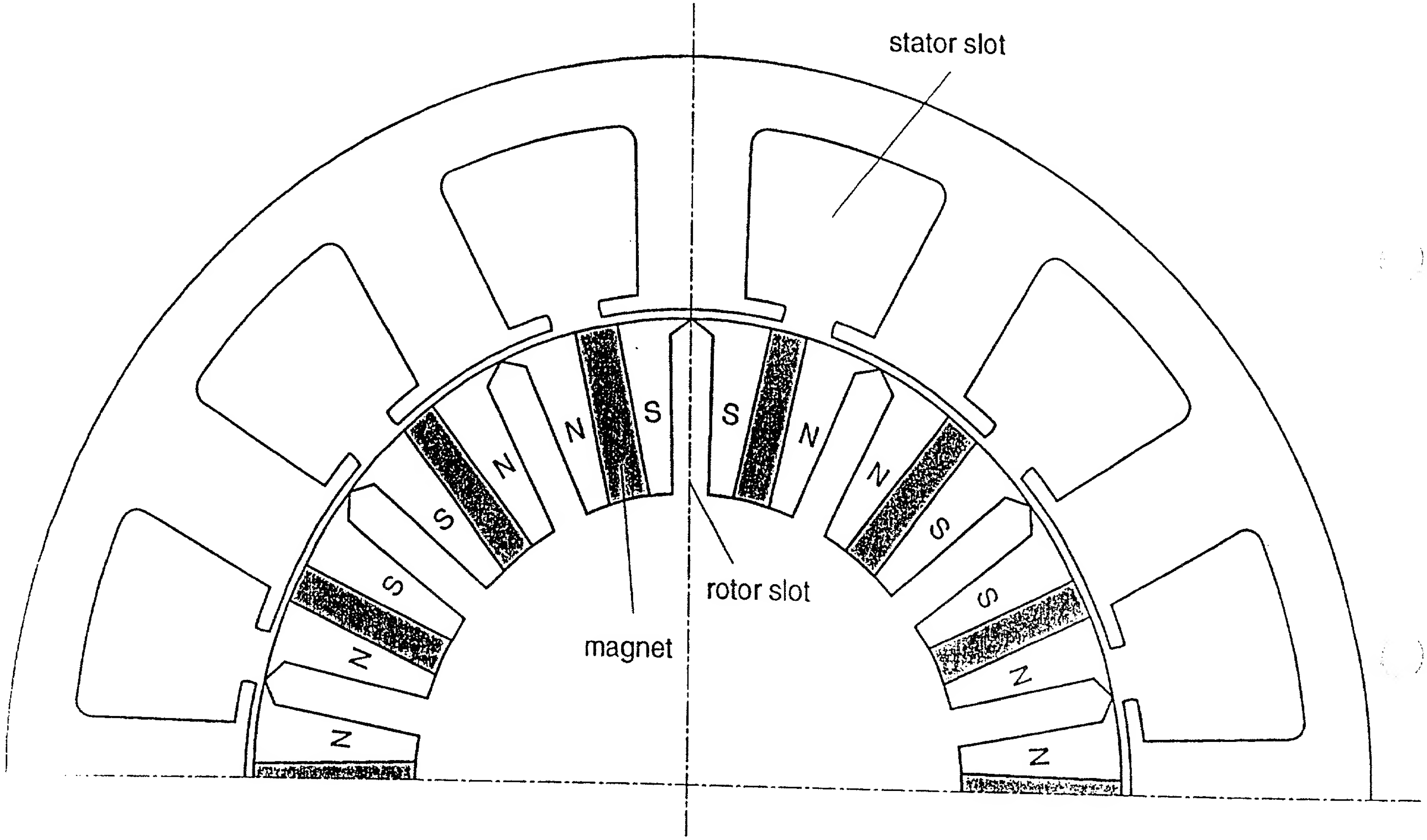
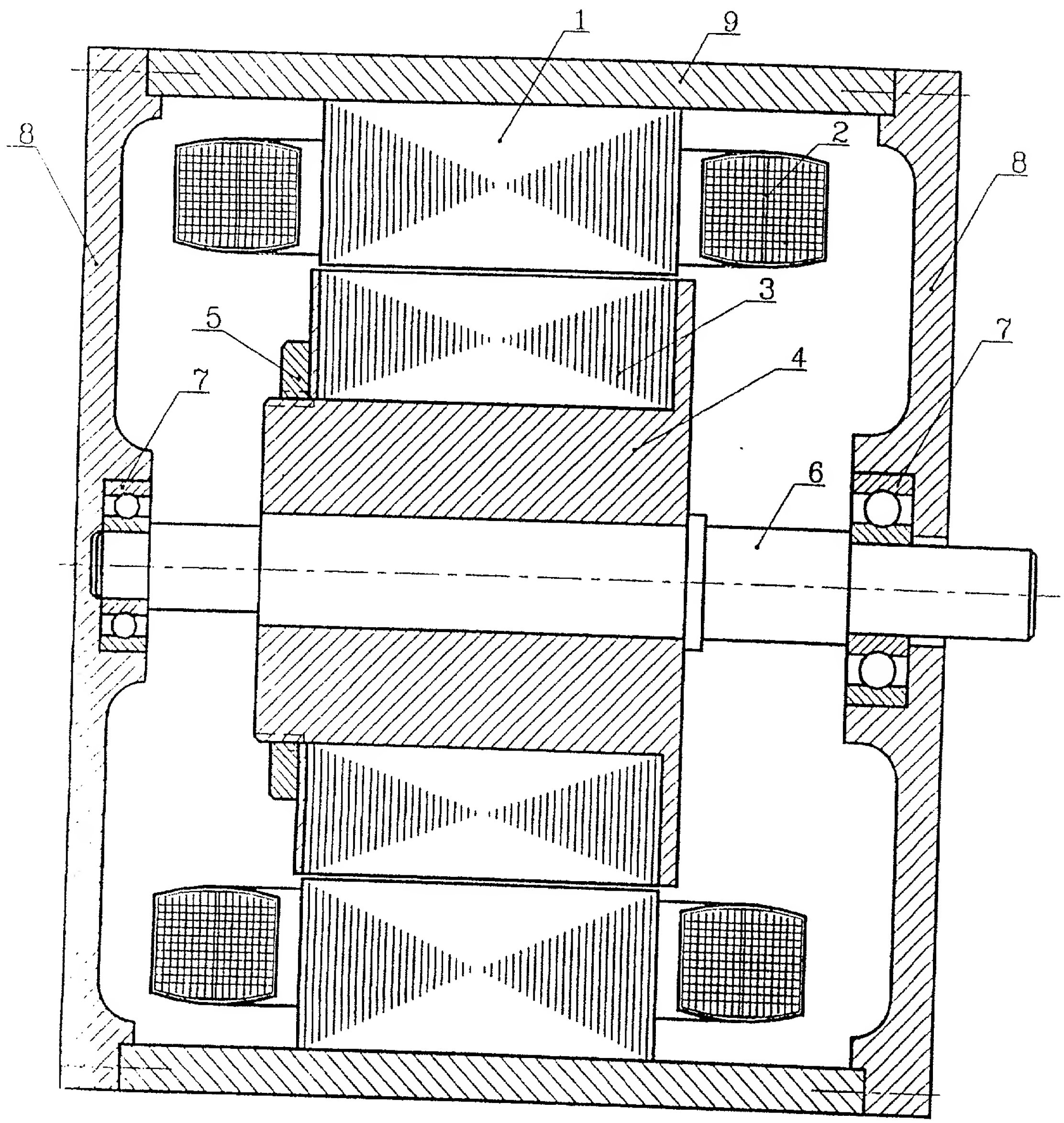
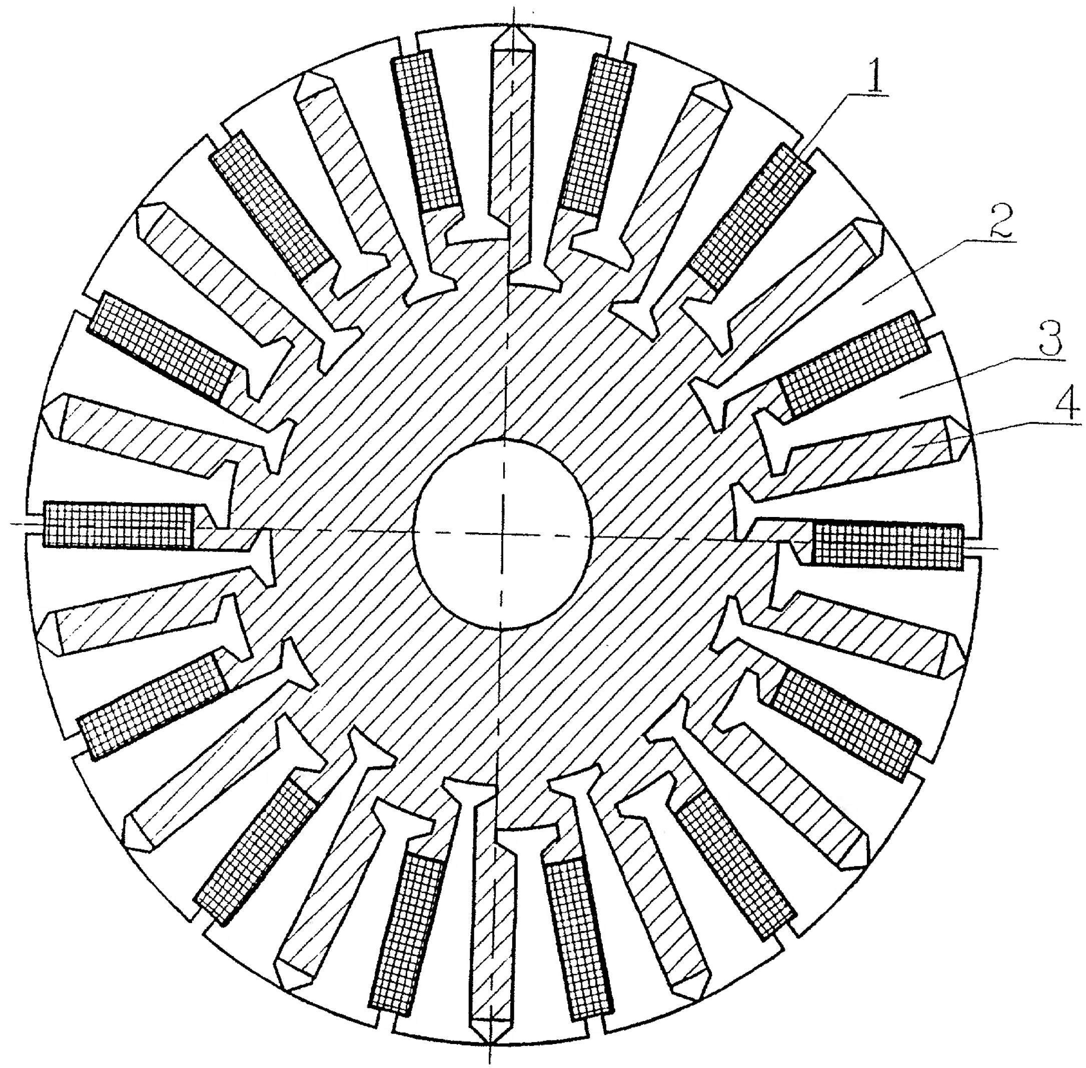


Fig 3 Schematic diagram of stator and rotor



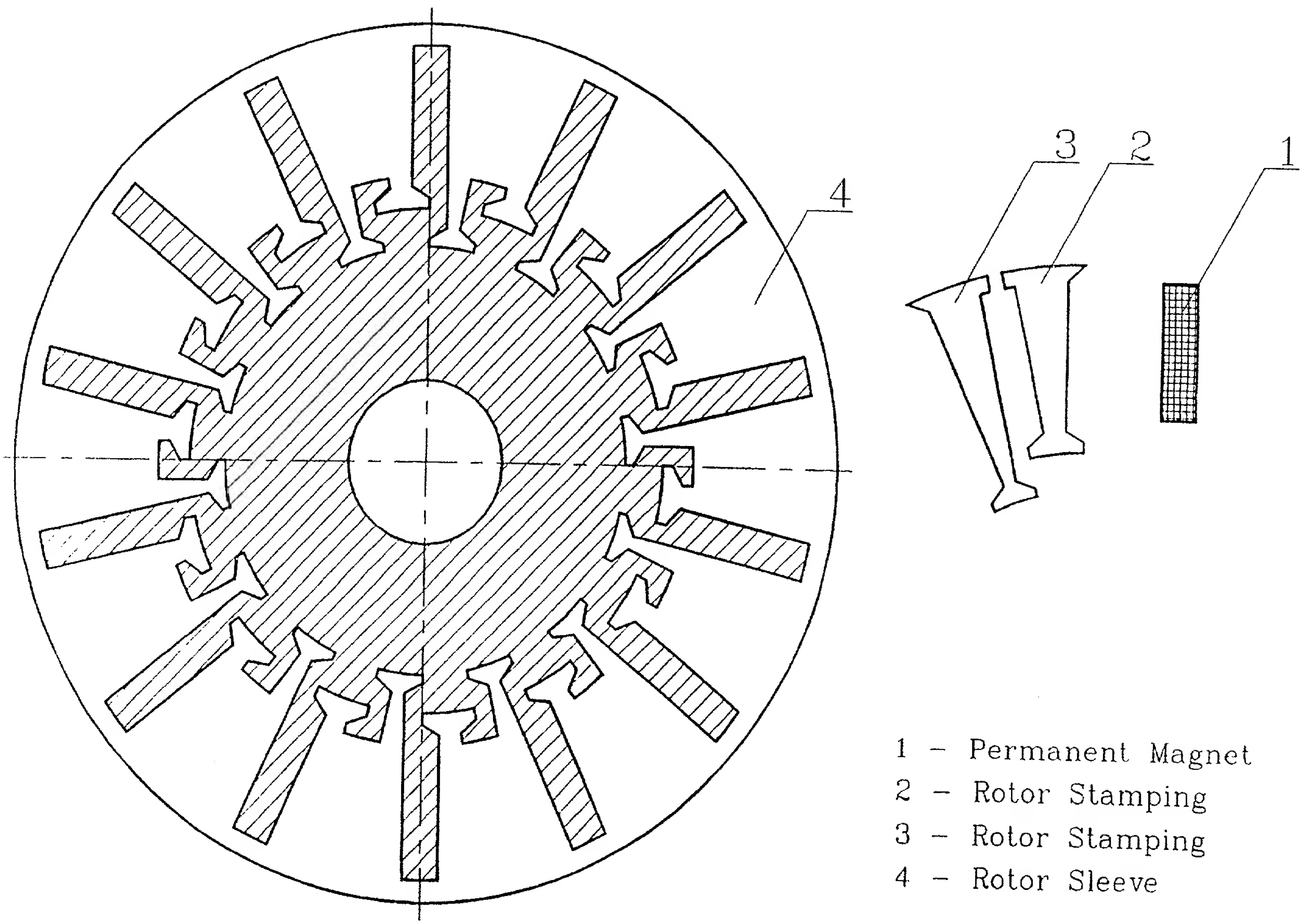
1 – Stator iron core
2 – Stator winding
3 – Rotor iron core
4 – Rotor sleeve
5 – Nut
6 – Shaft
7 – Bearings
8 – End brackets
9 – Frame

Fig. 4 Motor Assembly



1 - Permanent Magnet
2 - Rotor Stamping
3 - Rotor Stamping
4 - Rotor Sleeve

Fig. 5 Rotor Assemly



1 – Permanent Magnet
2 – Rotor Stamping
3 – Rotor Stamping
4 – Rotor Sleeve

Fig. 6 Rotor Components

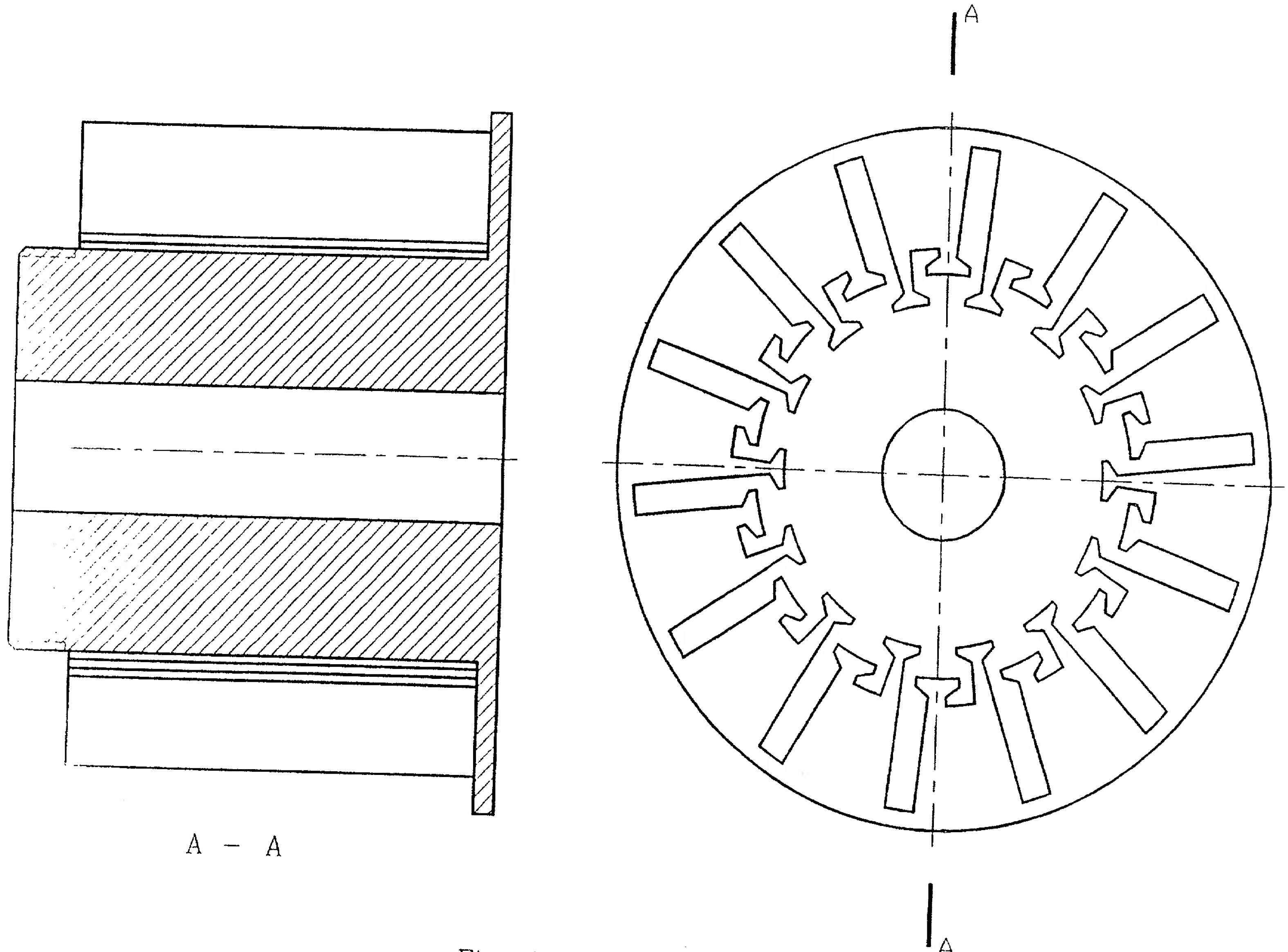


Fig. 7 Rotor Sleeve

(a) at constant torque region, $I_{af} = 0$, $\alpha = 0$

(b) at constant power region, $I = \sqrt{Iat^2 + Iaf^2}$, $\alpha \neq 0$

Fig 8 Phasor diagram

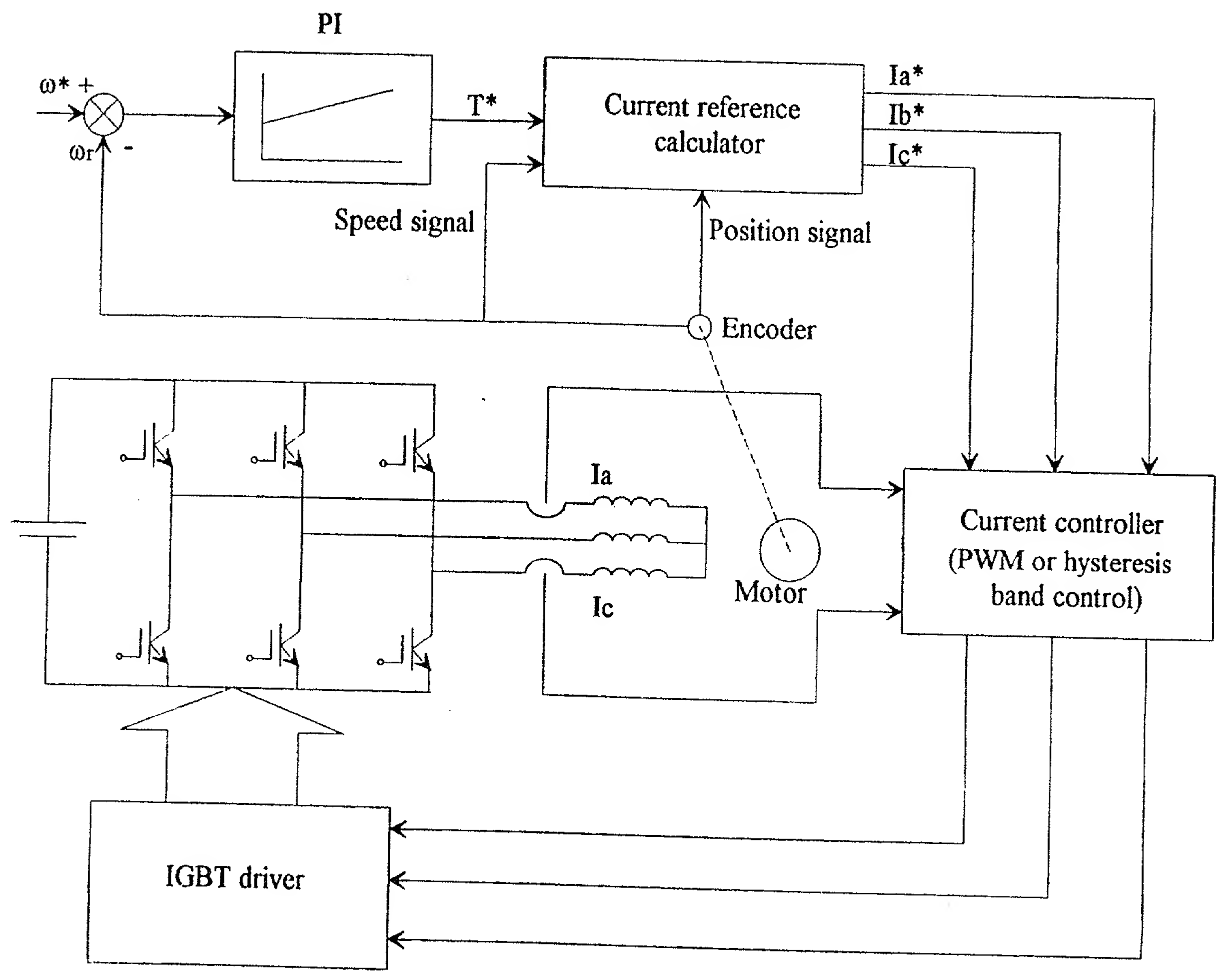


Fig. 9 Block diagram of control system

COMPLETE SPECIFICATION
A Novel Permanent Magnet Brushless DC Motor

I, CHING CHUEN CHAN, a professor of Electrical Engineering, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by it is to be performed, to be particularly described in and by the following statement:-

This invention relates to permanent magnet brushless dc motors or permanent magnet ac motors. The principles of operation of this kind of motors are already known. The magnetic flux of the motor is produced by permanent magnet and the communication is performed by electronic switches in accordance to the position of the rotor. The novelty of the motor lies in its unique electromagnetic topology and its unique control algorithm. The key factors are the selection of the number, configuration and co-ordination of stator slots, stator coils, and rotor magnets, as the following features :

(1) The number of rotor magnetic poles is designed to be nearly equal to the number of stator slots, usually $p = s \pm 2$, where p and s are the number of magnetic poles and stator slots respectively. Since the number of magnetic poles are large, the length of magnetic yoke, and hence the volume and weight of the motor are significantly reduced.

(2) The stator coil span is designed to be equal to one slot pitch, leading to minimise the overhang part of the coil, hence the copper used and motor weight are reduced while the motor efficiency is increased.

(3) The permanent magnets are mounted radially in the rotor as shown in Fig. 1, 3, and 5. Rotor slots are arranged between two magnets to reduce the armature reaction. The configuration of the rotor slots, stator slots and permanent magnets are optimized so that the magnetic flux produced by the permanent magnet is fully utilized for energy conversion at minimum loss.

(4) In conventional 3-phase permanent magnet brushless dc motor, there are 3-phase coils under one pole leading to resultant rotating flux produced by 3-phase current, hence 3-phase to d-q co-ordinate transformation is necessary for the speed control by vector control. However, in this invented motor, under each magnetic pole there is only one phase coil, hence the magnetic path of each phase flux is independent, thus co-ordinate transformation is not necessary for the vector control.

Fig. 1 shows the basic configuration and principles of the invented motor of 3-phase, 14-pole, 12-slot. The winding is a single layer winding with its coil span equals to slot pitch. There are totally 12 coils, each phase has 2 coils. Phase A consists of coils 1-2 and 8-7, while Phase B consists of coils 5-6 and 12-11, and Phase C consists of coils 4-3 and 9-10. The winding diagram and the positive direction of the current in the 3-phase windings are shown in Fig. 2

At the instant $t = o$ (see Fig. 1 b and c), phase A current is maximum value + Im while phase B current and phase C current are -Im/2. The directions of the currents in the conductors are shown in Fig. 1a. It can be seen that all currents in slots under S-poles flow towards the reader and all currents in slots under N-poles flow away from the reader. The interaction of flux and current produces torque which is anti-clockwise direction. After the rotor rotates 120^0 electrical degree, phase B current reaches maximum + Im, while phase **A** current and phase **C** current will be -Im/2, it can be derived that the magnitude and direction of the torque is the same, so as the case when the rotor rotates again 120^0 electrical degree and phase C current reaches +Im. Thus, likewise in synchronous machines, the motor speed can be controlled by adjusting the current frequency. If a rotor position sensor, as shown in Fig. 1a, is adopted to control the commutation of the three phase currents, the motor operates as brushless dc motor. The direction of rotation can be controlled by changing the phase sequence.

In order to achieve compact rotor construction (see Fig. 5), the rotor consists of the following components : the rotor sleeve 4 made by aluminium or non magnetic material, the stampings 2 and 3 made by electric steel sheets, and the permanent magnets 1. To assemble the rotor, the sleeve is mounted on the shaft, the stampings 2 and 3 are then mounted onto the sleeve. After that, the magnets are slide into the slots formed by stamping 2 and 3. Two-end plates are mounted at both sides to hold the stampings and magnets together onto the shaft by screw and nut or other means, as shown in Fig. 4.

The basic equations of the motor can be written as follows :

$$V = E + I\,(r + j\,X_s) \qquad \text{(1a)}$$

$$\approx E + j\,I\,X_s \qquad \text{(1b)}$$

$$E = k\,\phi\,\omega \qquad \text{(2)}$$

$$T = k\,\phi\,I_{at} \qquad \text{(3)}$$

$$I = \sqrt{I_{at}^2 + I_{af}^2} = I\,e^{j\alpha} \qquad \text{(4)}$$

$$\alpha = \operatorname{arctg}\frac{I_{af}}{I_{at}} \qquad \text{(5)}$$

where :

- V - voltage
- E - electromotive force (induced by the permanent magnet flux)
- r - armature resistance
- X_s - synchronous reactance
- k - constant
- ϕ - flux produced by permanent magnet
- I - armature current
- I_{at} - torque component current
- I_{af} - field component current

At constant torque operation, the field component current I_{af} is adjusted to zero, thus $I = I_{at}$, the phasor diagram is shown in Fig. 8a.

At constant power operation, the phase current equals to the vector sum of torque component current and field component current, $I = \sqrt{I_{at}^2 + I_{af}^2}$, the phasor diagram is shown in Fig. 8b.

A novel control algorithm may be adopted for speed control of the invented motor. As described earlier, the magnetic path of the flux produced by each phase is independent, therefore the magnetic flux and torque can be separately controlled easily by adjusting the phasor angle and amplitude of each phase current without co-ordinate transformation, since the field component current I_{af} and the torque component current I_{at} directly represent the flux and the torque respectively (see Equations 3 to 5 and Fig. 8). Fig. 9 shows the block diagram of the control system. According to the speed command, the current reference calculator calculates the reference current magnitude and phasor. Through the comparison of the reference current and actual current, the desired current can be achieved by PWM or hysteresis band control. The motor is able to operate at constant torque and constant power regimes. Its maximum speed can reach three times of the base speed, and its efficiency can be optimized over the whole operating range.

In summary, the major advantages of the invented motor are as follows:

1. High power density is achieved by unique configuration of stator slots, stator coils, rotor slots and magnets, thus enable to fully utilize the magnetic field and current, resulting in saving the required iron core, copper and magnets.

2. High efficiency is achieved by optimizing the above design configuration to obtain minimum copper loss, iron loss and mechanical loss.

3. Wide speed range is achieved by controlling the phasor and magnitude of the phase current, i.e. the field component current and torque component current. This control algorithm can be easily implemented without co-ordinate transformation due to each phase magnetic path is independent.

CLAIMS

What I claim is :

1. A permanent magnet burshless dc motor having all the following novel construction : (i) the number of magnetic poles equals to the number of stator slots plus or minus two, (ii) the stator coil span equals to one slot pitch, and (iii) the magnetic path of flux produced by each phase current is independent.

2. A permanent magnet brushless dc motor substantially as herein before described with reference to the accompanying drawings.

3. Speed control at constant torque and constant power regimes is achieved by controlling the phasor and magnitude of the phase current, i.e. the field component current and torque component current.

5

Patents Act 1977
Examiner's report to the Comptrc under Section 17
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Databases (see below)
(i) UK Patent Office collections of GB, EP, WO and US patent specifications.

(ii)

Search Examiner
J COCKITT

Date of completion of Search
27 JULY 1994

Documents considered relevant following a search in respect of Claims :-
1, 2

Categories of documents

X: Document indicating lack of novelty or of inventive step.

Y: Document indicating lack of inventive step if combined with one or more other documents of the same category.

A: Document indicating technological background and/or state of the art.

P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages		Relevant to claim(s)
X	GB 2218857 A	(PAPST) see whole document for example Figure 1	1 at least
X	EP 0234663 A1	(PHILIPS) see whole document for example Figure 1	1 at least
X	EP 0160868 A2	(KABUSHIKI) see whole document	1 at least
X	US 5034670 A	(MITSUBISHI) see whole document	1 at least

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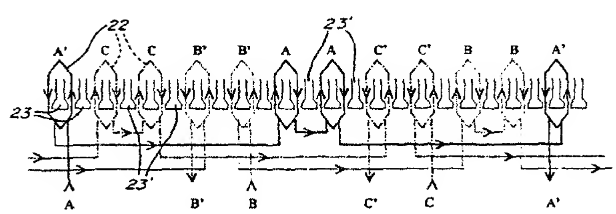
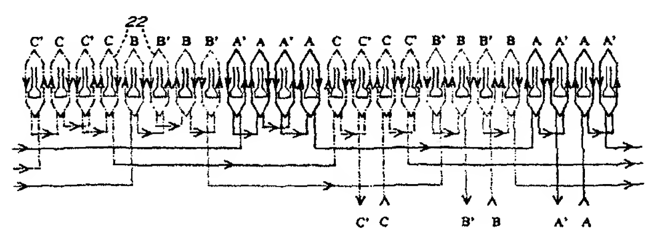
(54) Title: HIGH PERFORMANCE BRUSHLESS MOTOR AND DRIVE FOR AN ELECTRICAL VEHICLE MOTORIZATION





(57) Abstract: The system includes a permanent magnet three-phase motor and an electronic current controlled inverter by pulse width modulation. The motor has twenty-two poles and twenty-four slots, three phases and a cylindrical outer rotor. This structure minimizes torque ripple and maximizes energy efficiently. All coil windings are wound around the stator teeth. Several winding configurations are proposed and a special one with only one coil per slot. The motor phases are supplied by alternating rectangular current waveforms. A specific inverter control system is described to maximize efficiency and reduce current ripple and electromagnetic interference under motorizing or generating operations. The current control is realized by using the mosfets voltage for the current measurement.

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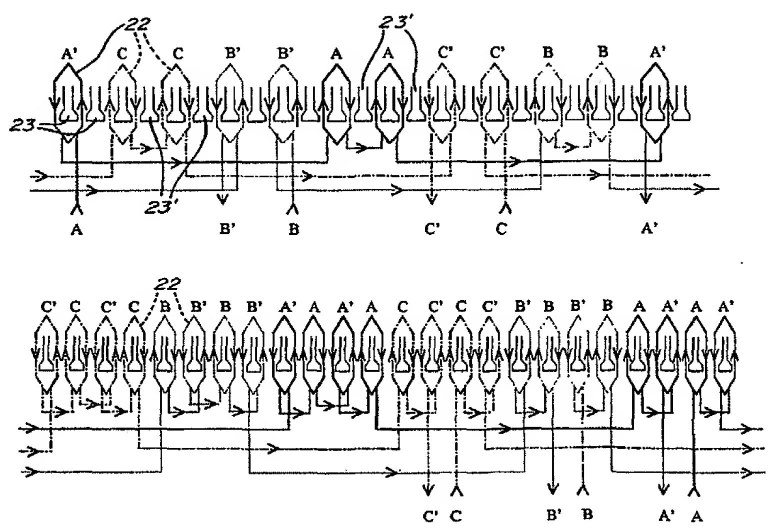

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